Top Quark Mass Measurement in ttbar All Hadronic channel at CDF

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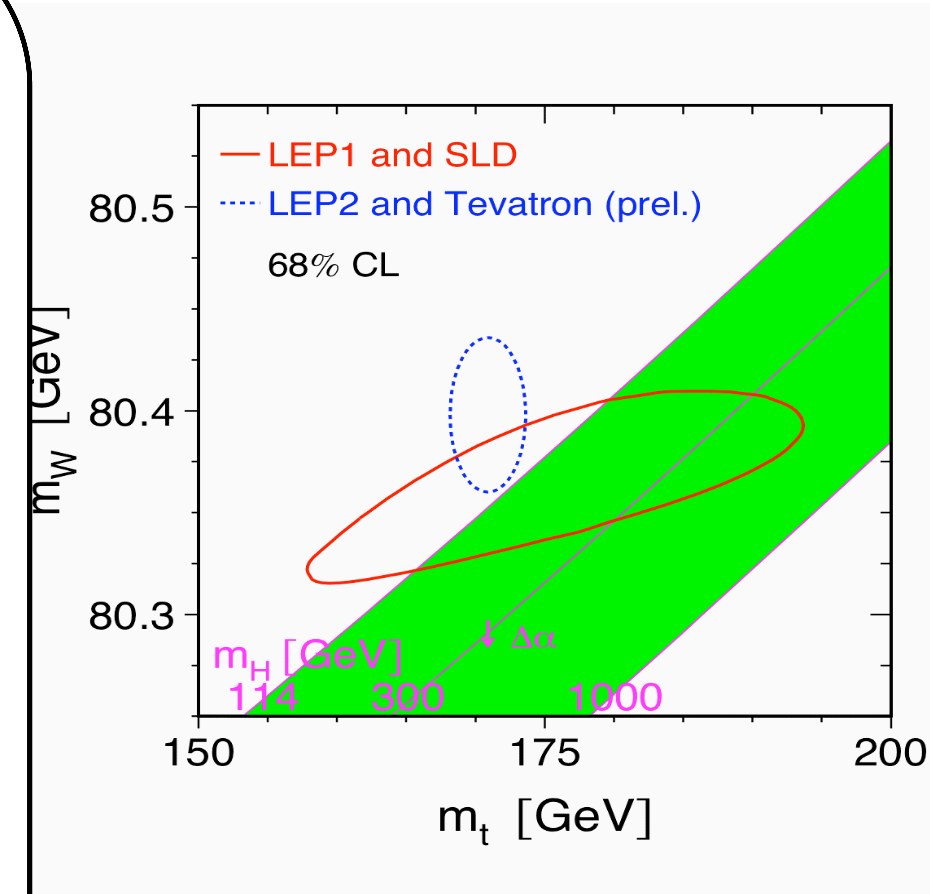
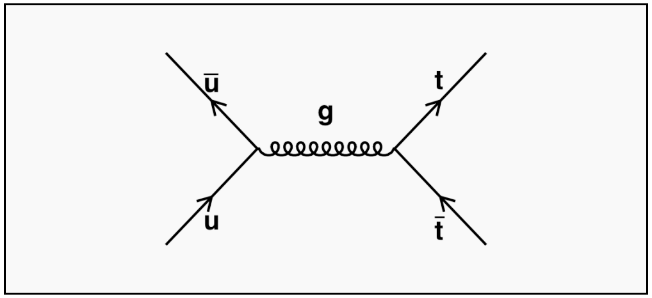
Top Quark Physics

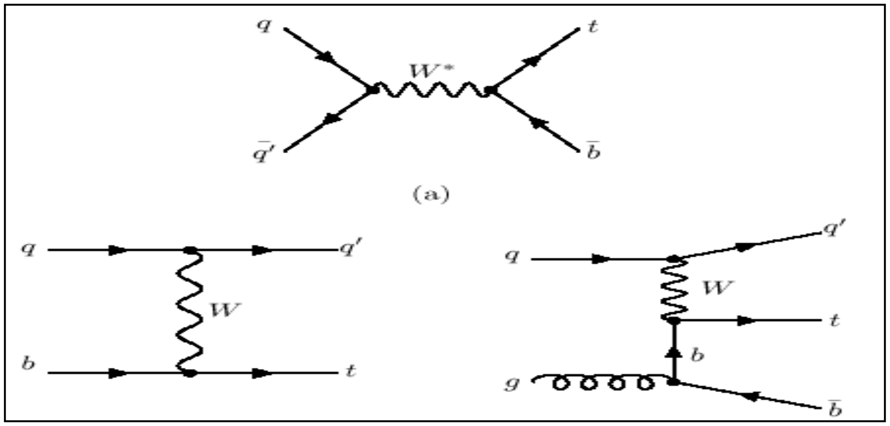
- What is "top quark"?
  - 3rd generation particle in Standard Model
  - Electric charge=2/3, Spin=1/2
  - Heaviest particle -> decays before hadronization (lifetime~4x10^{-25}s)
  - Passes momentum and spin information to its decay products
- *Motivation to study top*
  - Measuring its properties (mass, charge, spin, lifetime, etc) constrains theories aimed at fixing problems in Standard Model
  - Might have a special role in the dynamics of EWSB (Yukawa coupling ~1)
  - Knowing the mass of top quark constrains the mass of Higgs boson

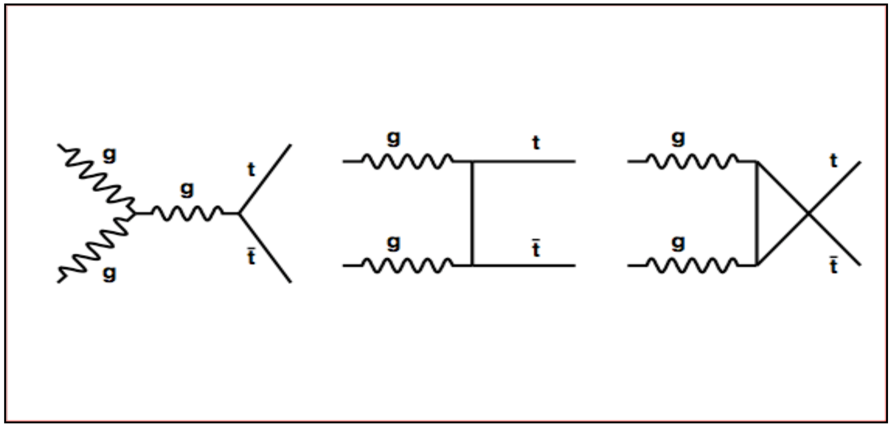


Producing Top Quarks

- *Main Mechanisms:*
  - Pair production
    - Quark-antiquark annihilation
    - Gluon-gluon fusion
  - Single top



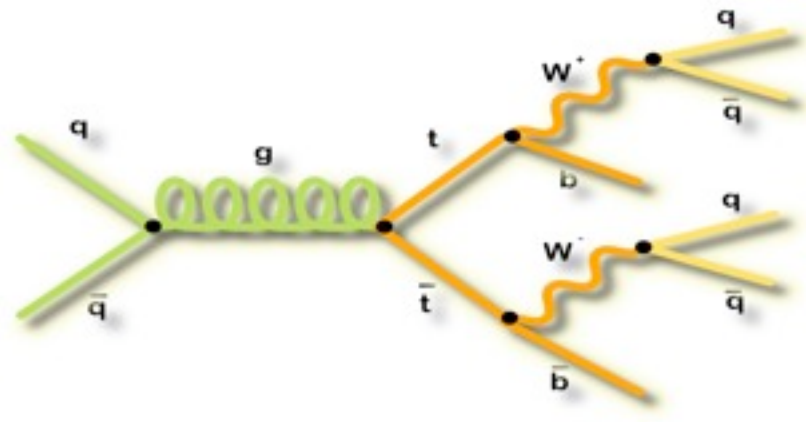


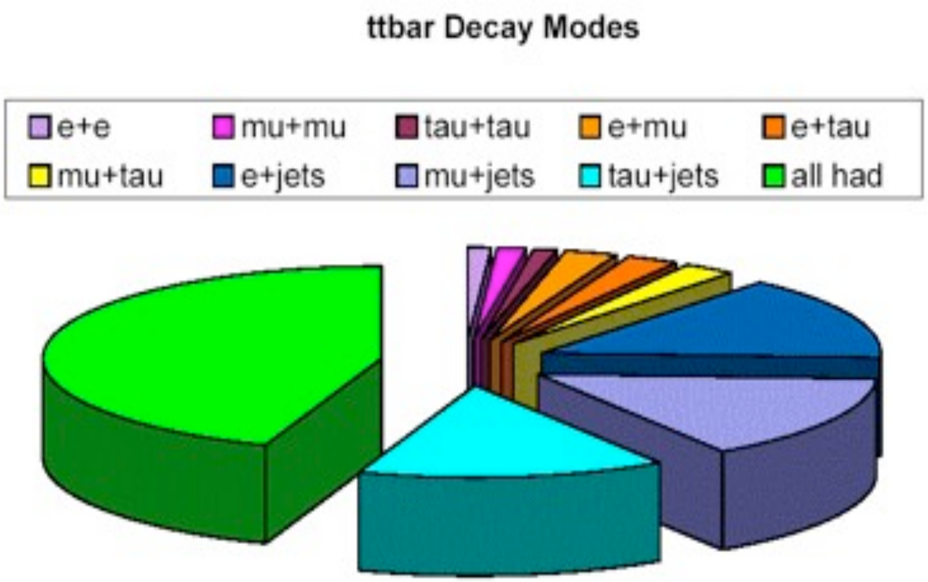


- *Experiments location*
  - *Tevatron*
    - Ppbar collider designed for top quark discovery
    - 1.96TeV in center-of-mass $\Rightarrow$ 15% gg fusion, 85% qqbar
  - *LHC*
    - pp collider
    - 14TeV in center-of-mass $\Rightarrow$ 90% gg fusion, 10% qqbar

Expected signature for ttbar pairs

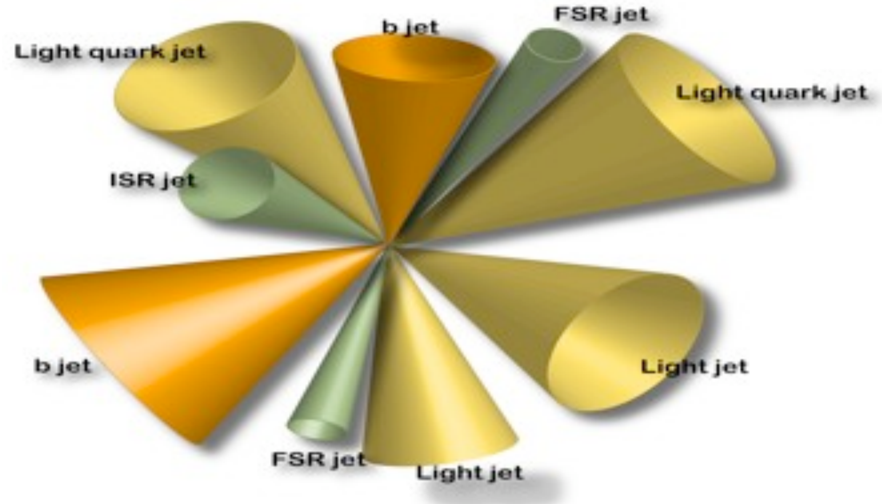
- Standard Model top quark decay
  - 99% of the time t -> W + b
  - W boson decays into:
    - Lepton pairs
      - $e+\nu_e$, $\mu+\nu_\mu$, or $\tau+\nu_\tau$
    - Quark pairs
      - (ud or cs) x 3 colors
- SM ttbar decay channels
  - Tau+X(lepton or quark) 17/81~21%
  - Dilepton: 4/81~5%
  - Lepton+Jets: 24/81~30%
  - All Hadronic: 36/81~44%

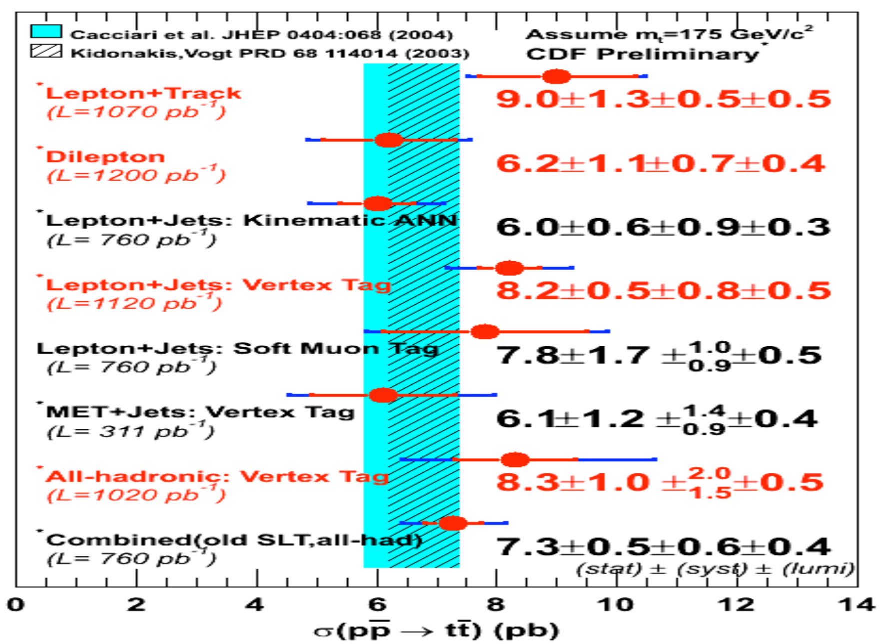




Top Quark in All Hadronic Channel

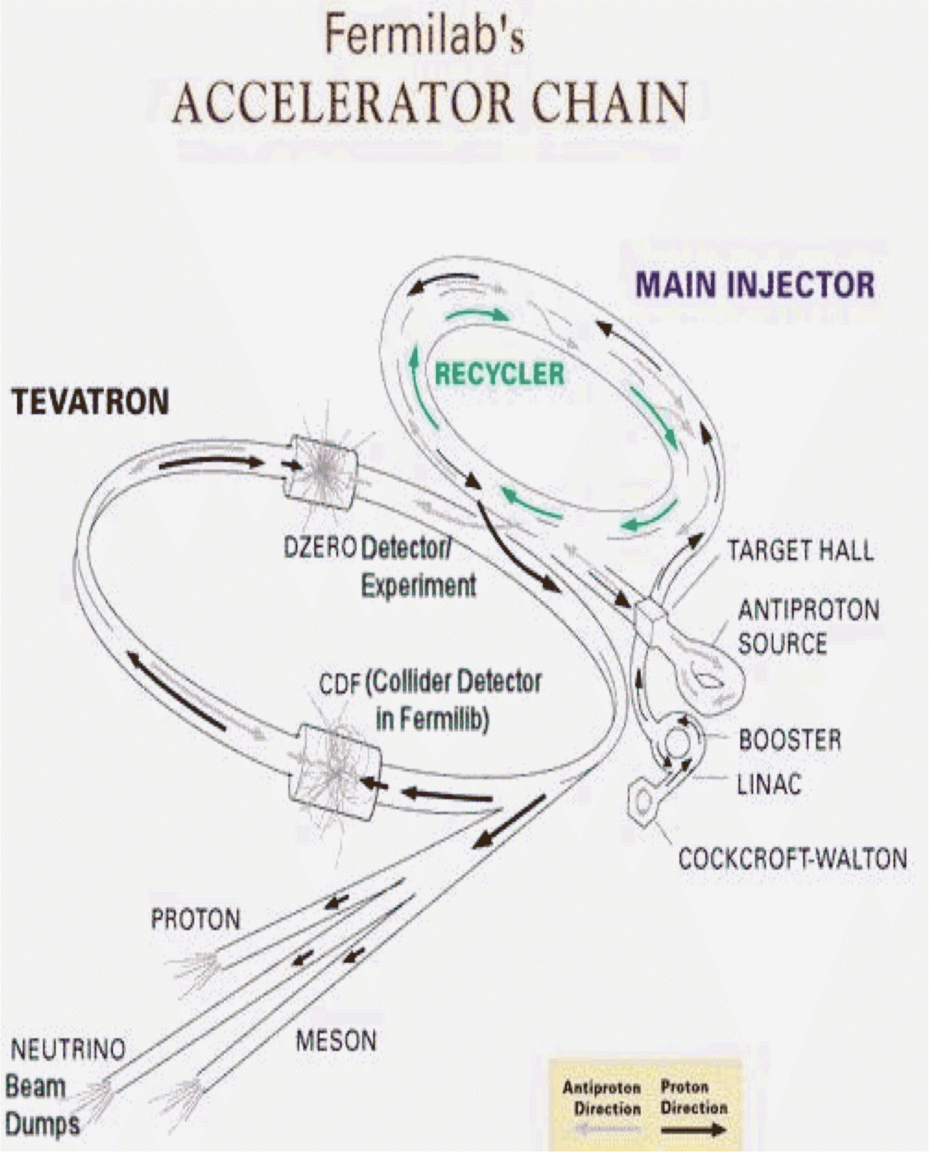
- Features
  - Largest branching fraction
  - Fully reconstructed final state
  - Large QCD multijet background
  - Large combinatorial background (ambiguity in quark-jet pairing)
  - Jet energy scale has big effect
- Motivation
  - Testing of the Standard Model
  - Consistency check among the ttbar decay channels
  - Improve uncertainties by using
    - New tools
    - New event selection
- Measurements in this channel
  - Cross-section measurement
    - Most recent: $8.3\pm^{2.3}_{1.9}$ pb
  - Mass measurements
    - Only 3 other results
    - Best: 174.5±5.3 GeV
  - Resonance search (in progress)





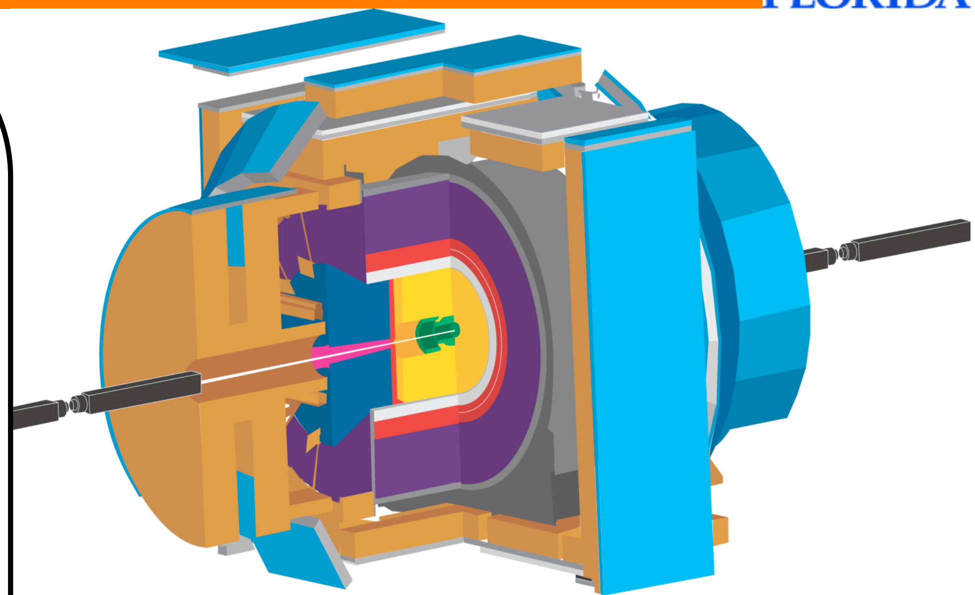
Tevatron

- Superconducting Proton and Anti-proton synchrotron
  1. Each beam has 3x12 bunches with 396ns bunch separation
  2. Superconducting magnets bend particles for a 21 μs revolution time around the 1km radius ring
  3. 8RF cavities accelerate particles to 980GeV (The most energetic accelerator collecting data to date)
  4. The beams collide at CDF & D0
- Instantaneous luminosity is of order 10^{31}-10^{32} $cm^{-2}s^{-1}$
  - record is 2.9×10^{32} $cm^{-2}s^{-1}$
- Integrated luminosity delivered:
  - present: ~$3.2 fb^{-1}$ (goal ~ $8 fb^{-1}$)



Collider Detector at Fermilab

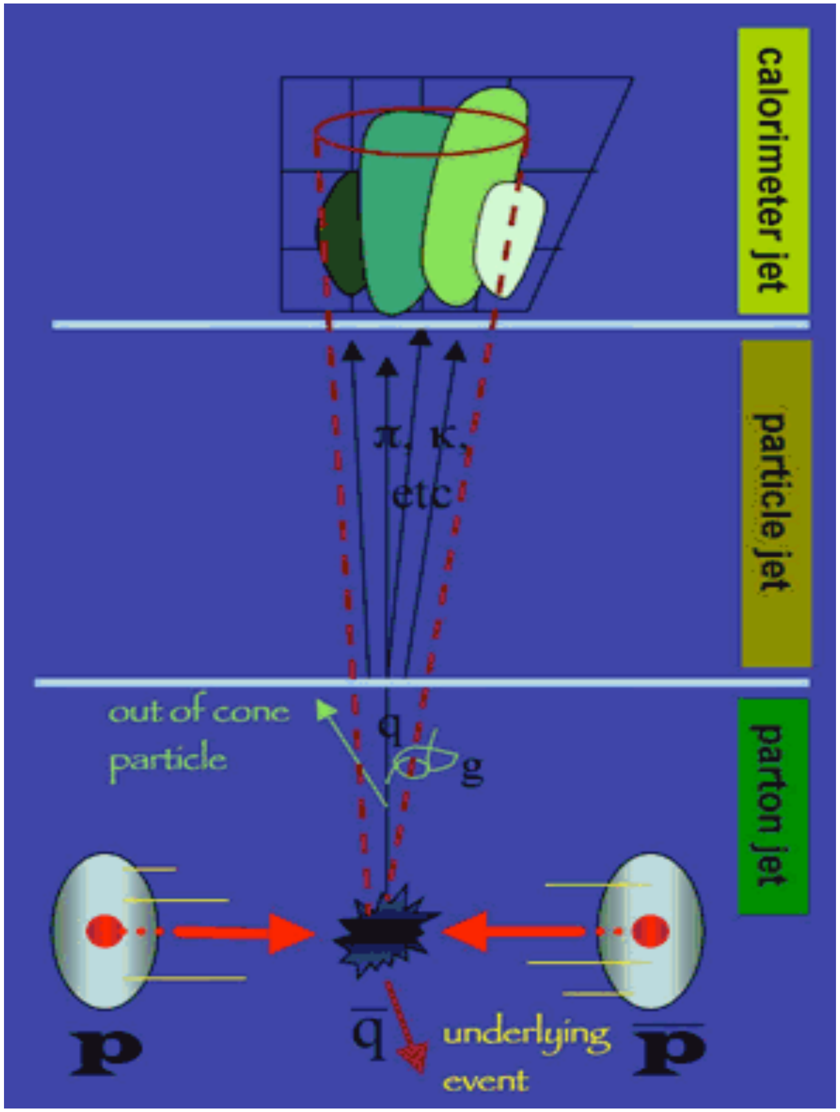
- Multi-purpose detector with subsystems placed around beam pipe
- Silicon detector
  - 30-60μm resolution for impact parameter of tracks
- COT-Central Outer Tracker
  - Open-cell wire drift chamber
  - Hit position resolution~140μm
  - Momentum resolution~0.0015 GeV^{-1}
- Time-of-Flight detector
  - Separates kaons and pions (~100ps)
- Calorimeters
  - Segmented sampling sandwich of metal & scintillators
  - EM (Pb) (13.5%/sqrt(E_T)$\oplus$2%)
  - Hadronic (Fe) (75%/sqrt(E_T)$\oplus$3%)
- Muon system
  - 4 drift chambers
- Trigger and Data acquisition
  - Three trigger levels -> ~100Hz
- 1 pair of top-antitop every 10^{10} collisions



- Luminosity detector-CLC
  - 96 Cherenkov counters filled with isobutane
  - $3.7 < |\eta| < 4.7$
  - Determines luminosity by counting the average number of inelastic ppbar interactions
    - $L=\mu \cdot f_{bc}/\sigma_{inel}$
  - I was part of the group monitoring and maintaining CLC

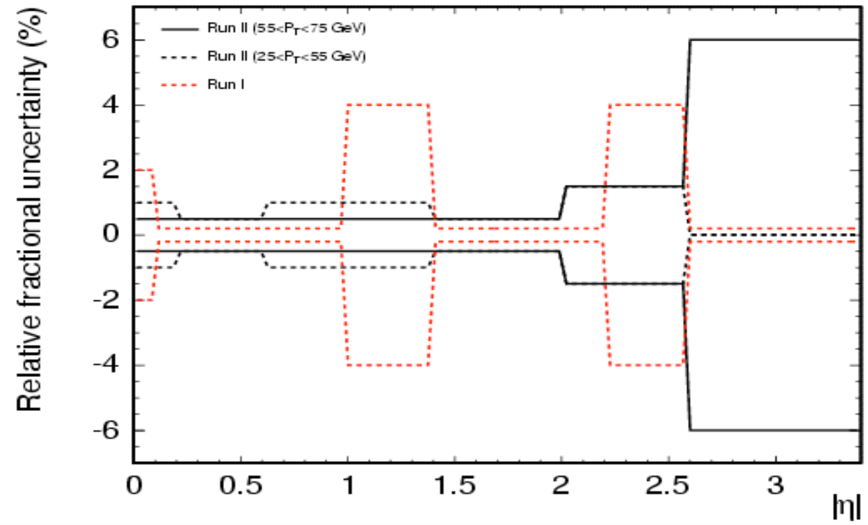
Determining Jet Energies

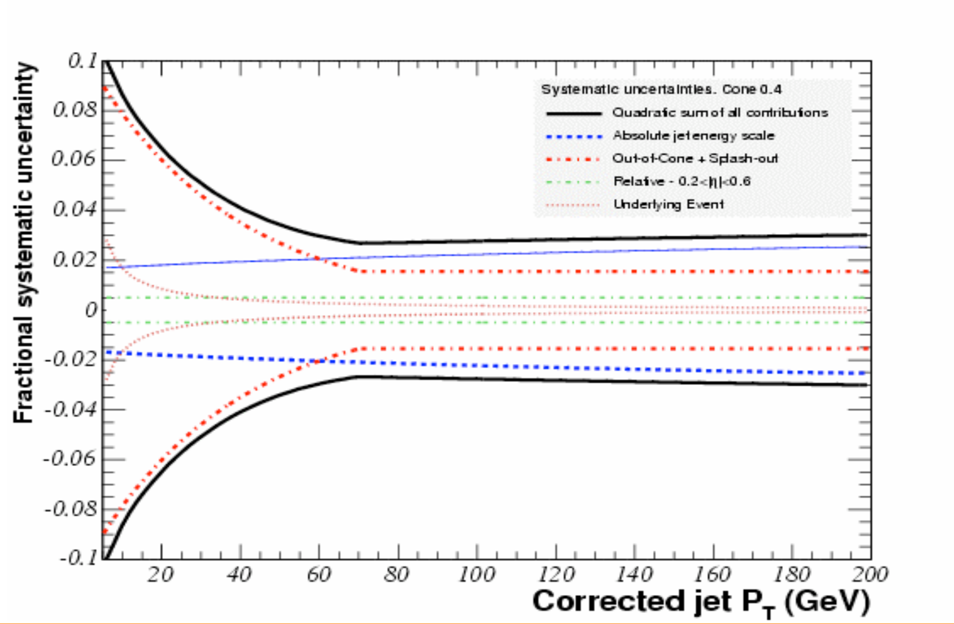
- Jet
  - collection of particles generated by the hadronization of a parton followed by the fragmentation/decay of the hadron(s).
- Jet Energy
  - deposited in the calorimeter
  - understood as the sum of energies of all particles
  - needs to be corrected due to various effects



Correcting Jet Energies

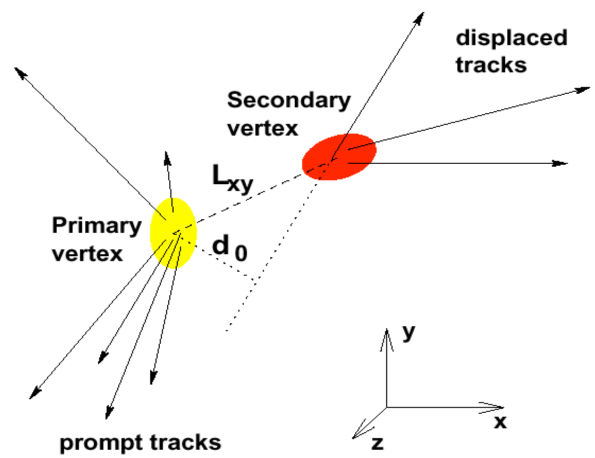
- Jet Energy Corrections
  - Relative scale
    - Scales the forward regions to the central part
    - Di-jet & photon-jet balance
  - Absolute scale
    - Non-linearities & energy loss from un-instrumented regions
    - Use Monte Carlo simulation
  - Multiple interactions
    - Subtract the energies of particles coming from different interaction
    - Uses minimum bias data
  - Underlying event
    - Subtract the energies of spectator particles
    - Uses minimum bias data
  - Out-of-cone
    - Adds energy not clustered by the jet algorithm
    - Use Monte Carlo simulation
- *Interesting to check this scaling in ttbar events*

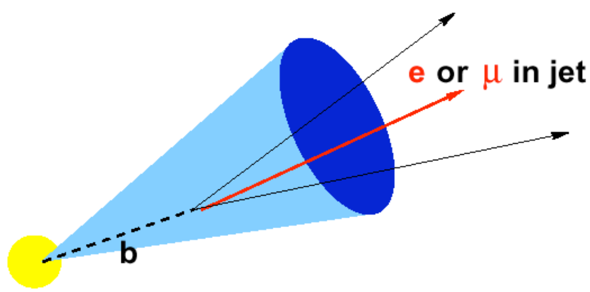




Heavy Flavor Jet ID

- ***Identification of such jets reduces backgrounds for top quark signal***
- Secondary vertex algorithms
  - SecVtx and JetProbability
  - Lifetime ~10ps means travel distance ~3mm
  - Silicon detector resolution allows for such measurements
  - *For JP, I have studied how the ID rates depend on various parameters*
- Soft lepton finder algorithms
  - Identifies a soft electron/muon within the cone of a reconstructed jet

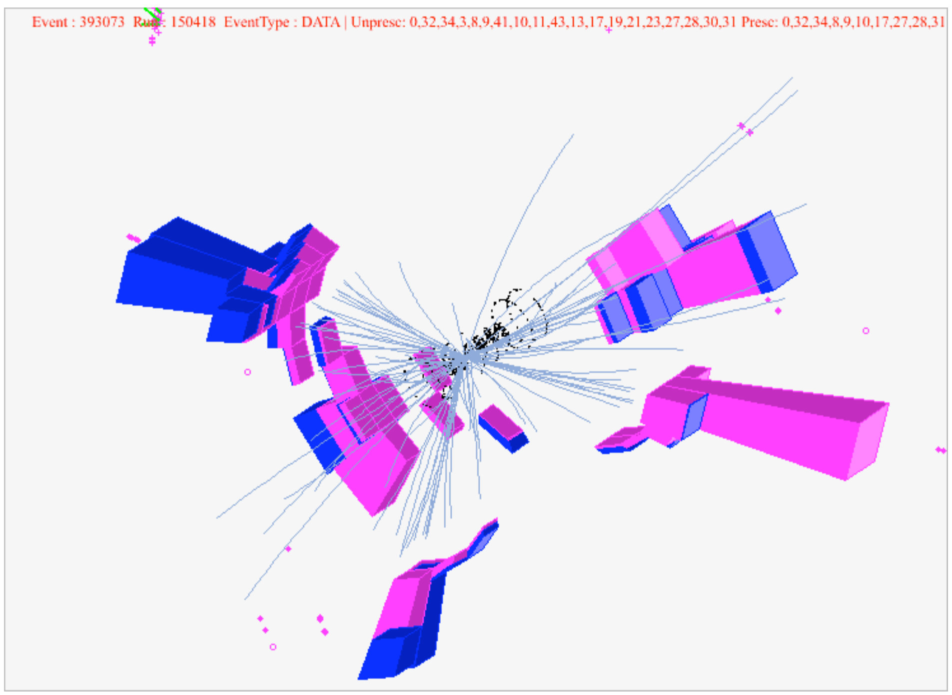




- $b \to \ell \nu c$ (BR $\sim$ 20%)
- $b \to c \to \ell \nu s$ (BR $\sim$ 20%)

Data sample

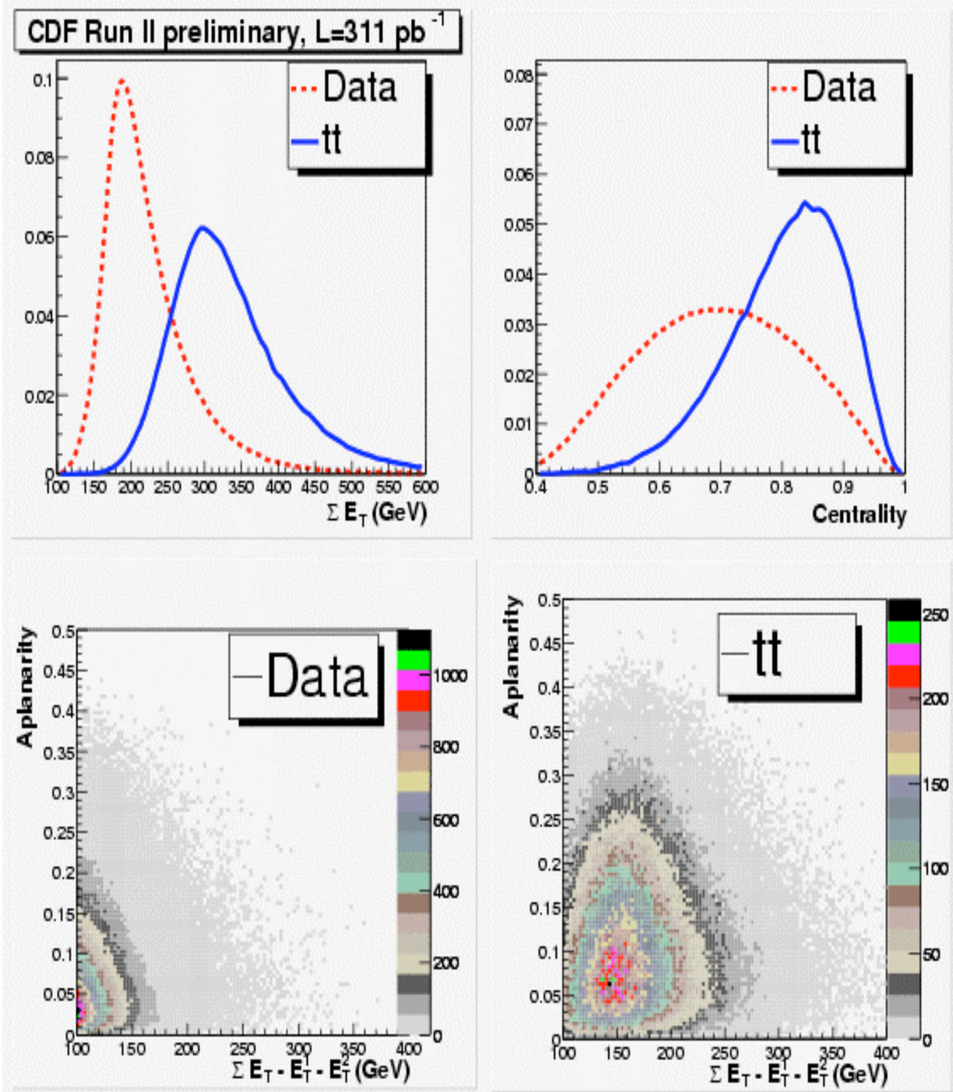
- Data sample
  - 943 pb^{-1} of multijet events [use a trigger 88% efficient for ttbar all hadronic events]



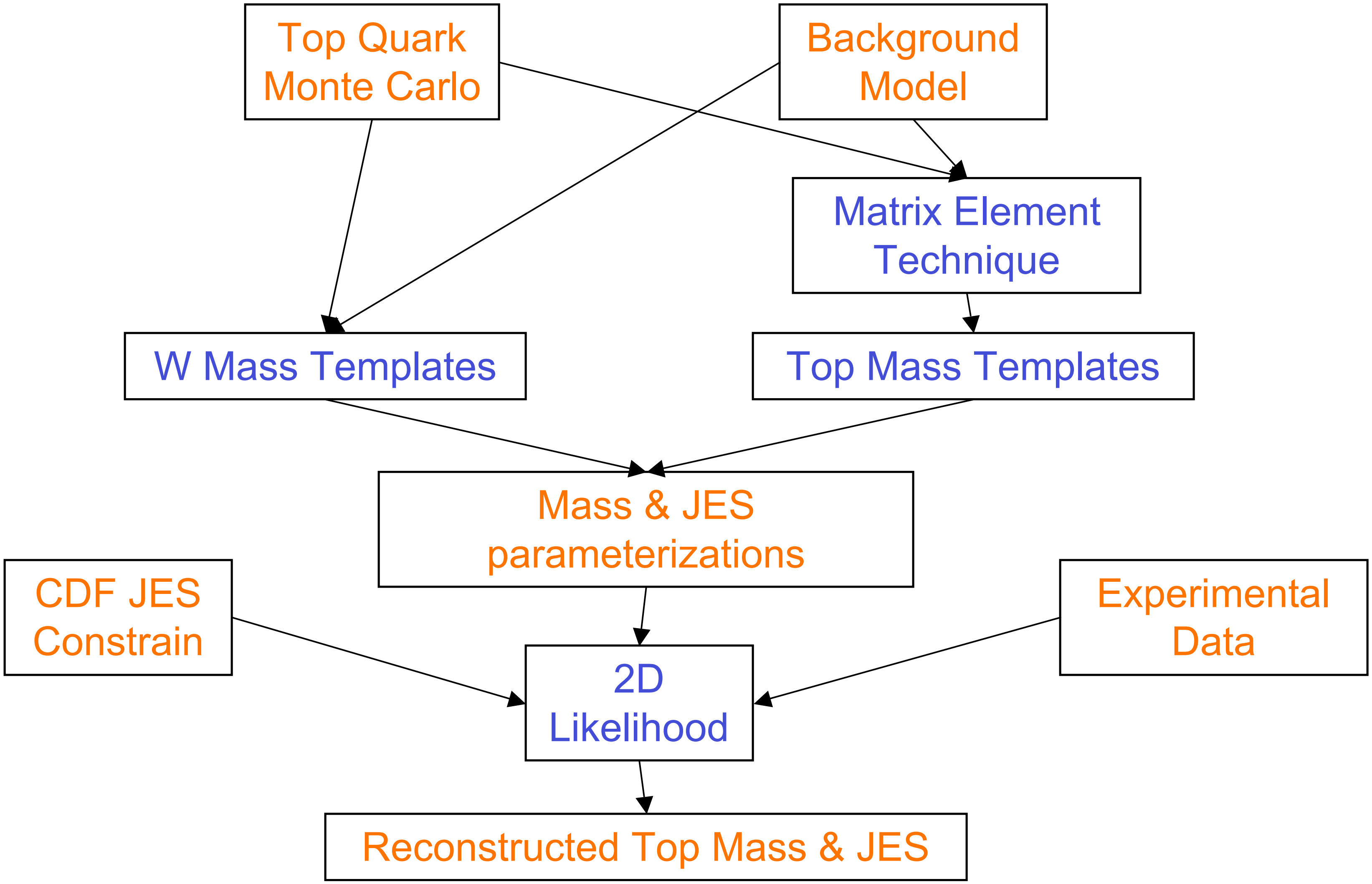
- **Sample composition**
  - Signal- ttbar all hadronic
    - has 6 quarks in the final state which will hadronize into 6 jets of particles [xs~3pb].
    - very energetic, central and spherical
    - Two of the quarks are b-quarks -> heavy flavor jets
  - Background:
    - QCD multijets
      - Bb+4 partons [xs~48nb]
      - 6 partons [xs~830nb]
    - Hadronic W/Z+jets [xs~2.8nb]
    - Single top+radiation [xs~2pb]
    - Hadronic W/Z pairs+radiation [xs~5pb]

Preliminary Event Selection

- **Clean-up cuts -> S/B ~ 1/1300**
  - Trigger emulation: Level2 SumEt>175GeV
  - Vertex: $|z|<60$cm & $|z-z_p|<5$cm
  - Missing Et Significance: $< 3\ (\mathrm{GeV})^{1/2}$
  - Tight lepton veto
- **Kinematical cuts -> S/B ~ 1/23**
  - Njets = 6 jets with |eta|<2 & Et>15GeV
  - Aplanarity+0.005SumEt$_3$ > 0.96
  - Centrality > 0.78
  - SumEt > 280GeV
- **B-tagging -> S/B ~ 1/6**
  - Require at least 1 heavy flavor jet
  - Use SVX tagger

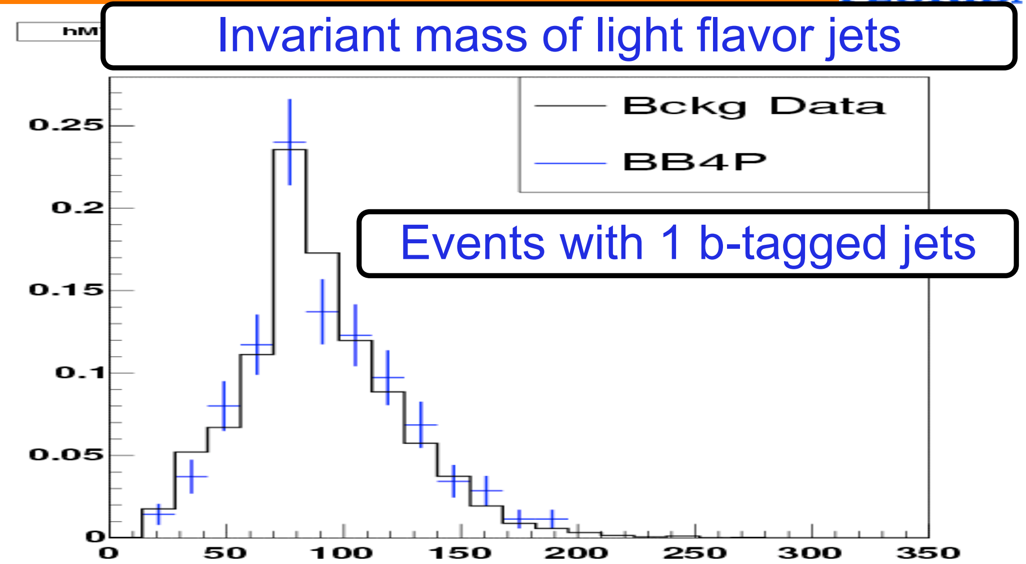


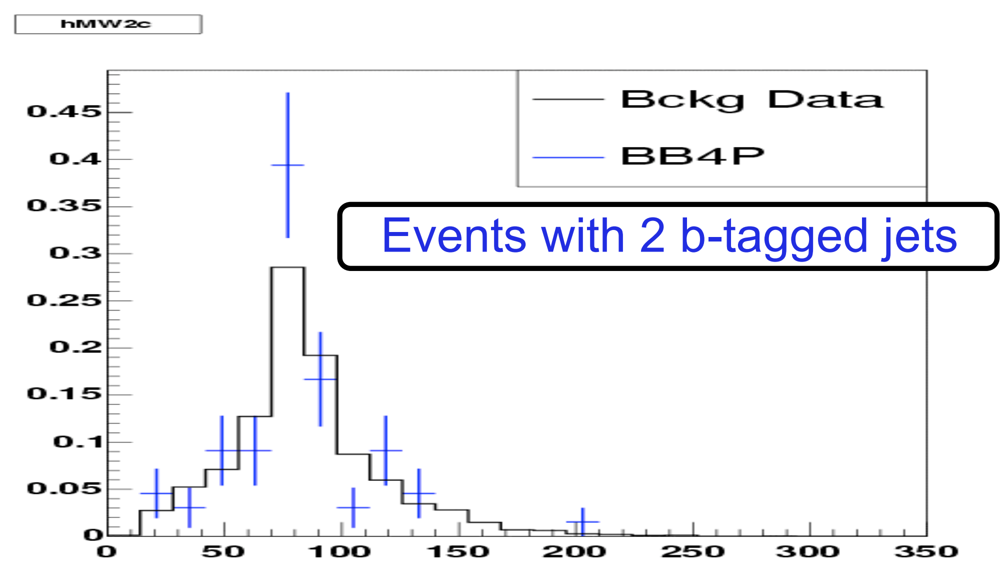
Analysis Flow Chart



Background Model

- .Method
  - *Parameterize the heavy flavor jet rates from a background dominated sample*
  - Extrapolate the rates above to the signal region
  - *Check shapes with Alpgen background Monte Carlo*
  - Normalization is determined by subtracting the signal expectation from the data
- For $943 pb^{-1}$ of data, the background estimate is
  - 35 single tagged
  - 10 double tagged





Matrix Element Technique

- Define the probability that a multijet event is produced via ***ttbar*** all hadronic mechanism at a given top mass.

- Ratio of the elementary cross-section for an 6-jet event defined by {j} to the total cross-section

$$dP(M_{top}) = \frac{d\sigma(j \mid M_{top})}{\sigma(M_{top})}$$

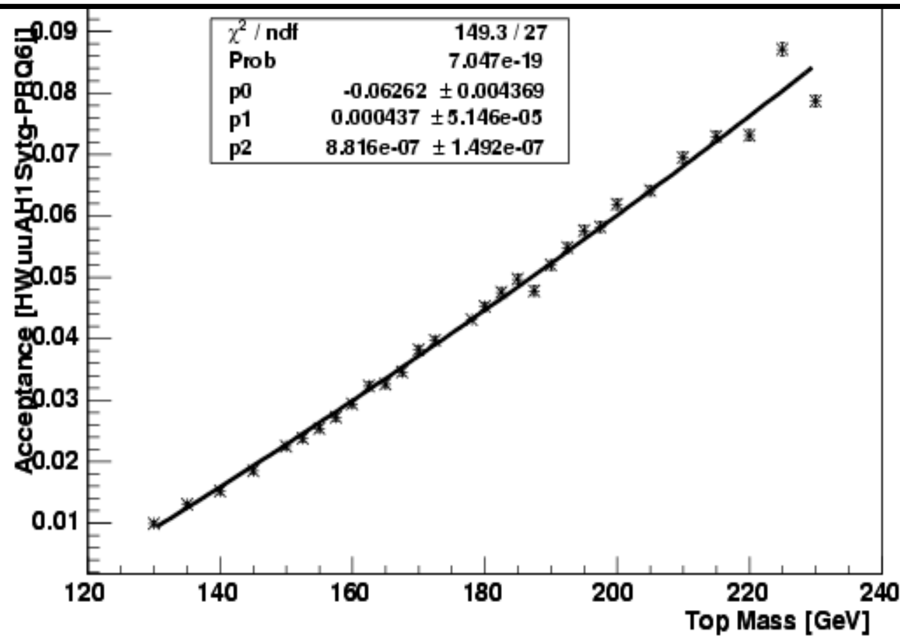
- More realistically:
  - Jet energies are not the true energies of the quarks
  - Need transfer functions to describe parton-to-jet transition
    - Help by enhancing the ttbar-likeness of the parton configuration using Pt of ttbar system as weight.
  - Ambiguity in parton-jet assignment -> combinations
  - Event selection means only a fraction ε(M) of total cross-section is used.

Event probability density expression: $$P(M_{top}) = \frac{\sum_{combi} \int d\sigma(p \mid j, M_{top}) \cdot TF(p \mid j) \cdot P_T(p)}{\sigma(M_{top})\varepsilon(M_{top})N_{combi}}$$

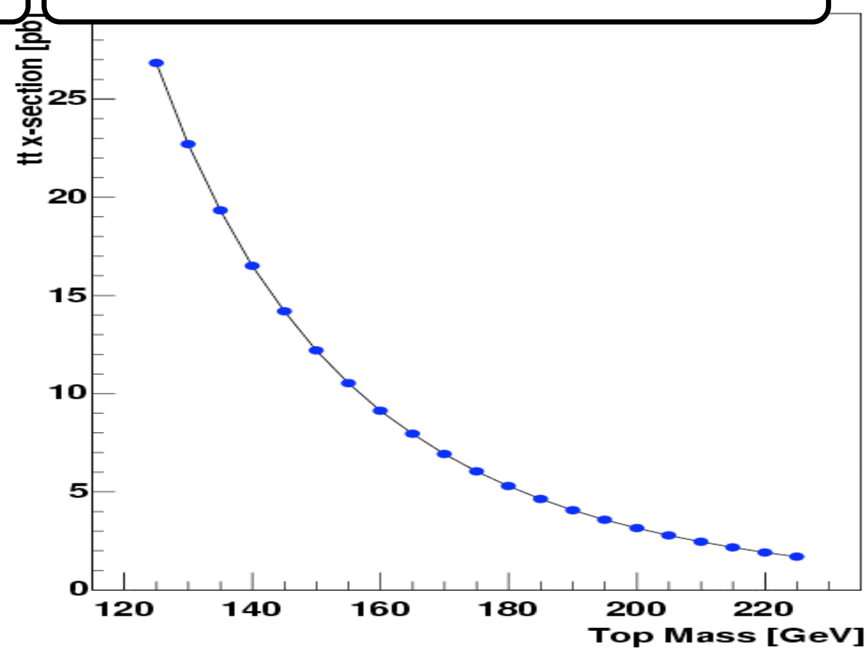
Probability Density Normalization

Event probability density expression: $P(M_{top}) = \dfrac{\sum_{combi} \int d\sigma(p \mid j, M_{top}) \cdot TF(p \mid j) \cdot P_T(p)}{\sigma(M_{top})\varepsilon(M_{top})N_{combi}}$

Fraction of ttbar events passing kinem. cuts



Total cross-section for ttbar events

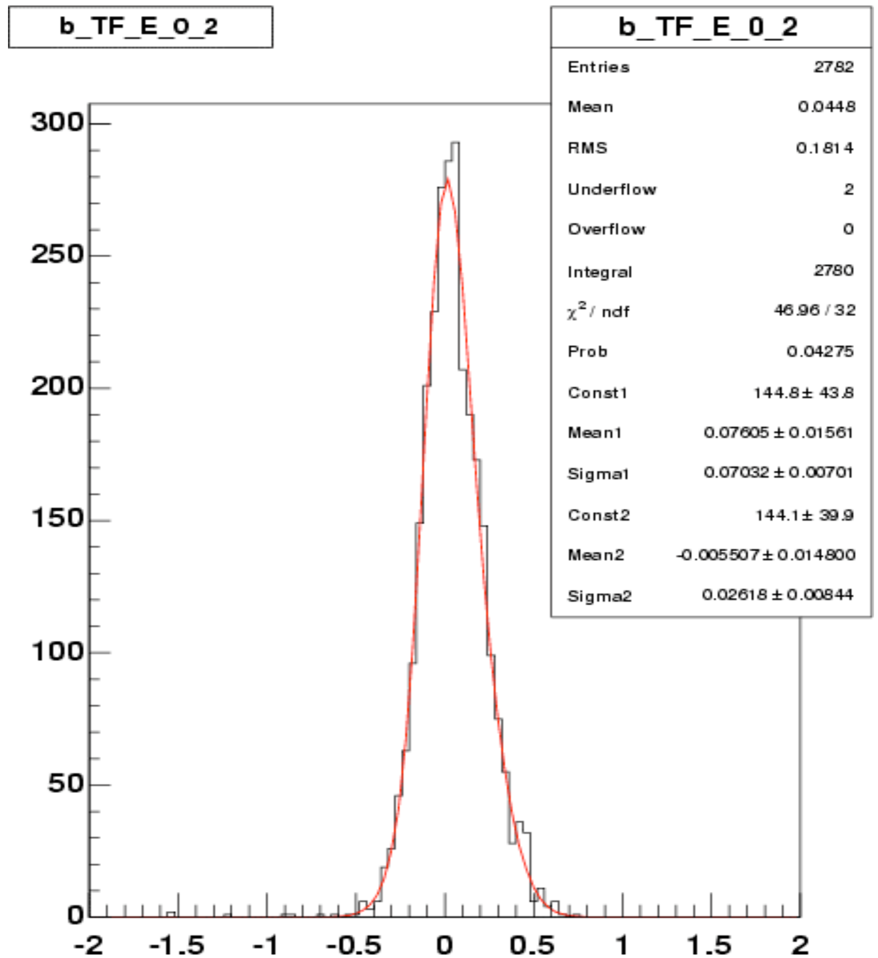


- **Number of combinations**
  - 120 for single b-tagged events
  - 24 for double tagged events

Transfer Functions

Event probability density expression: $$P(M_{top}) = \frac{\sum_{combi} \int d\sigma(p \mid j, M_{top}) \cdot TF(p \mid j) \cdot P_T(p)}{\sigma(M_{top})\varepsilon(M_{top}) N_{combi}}$$

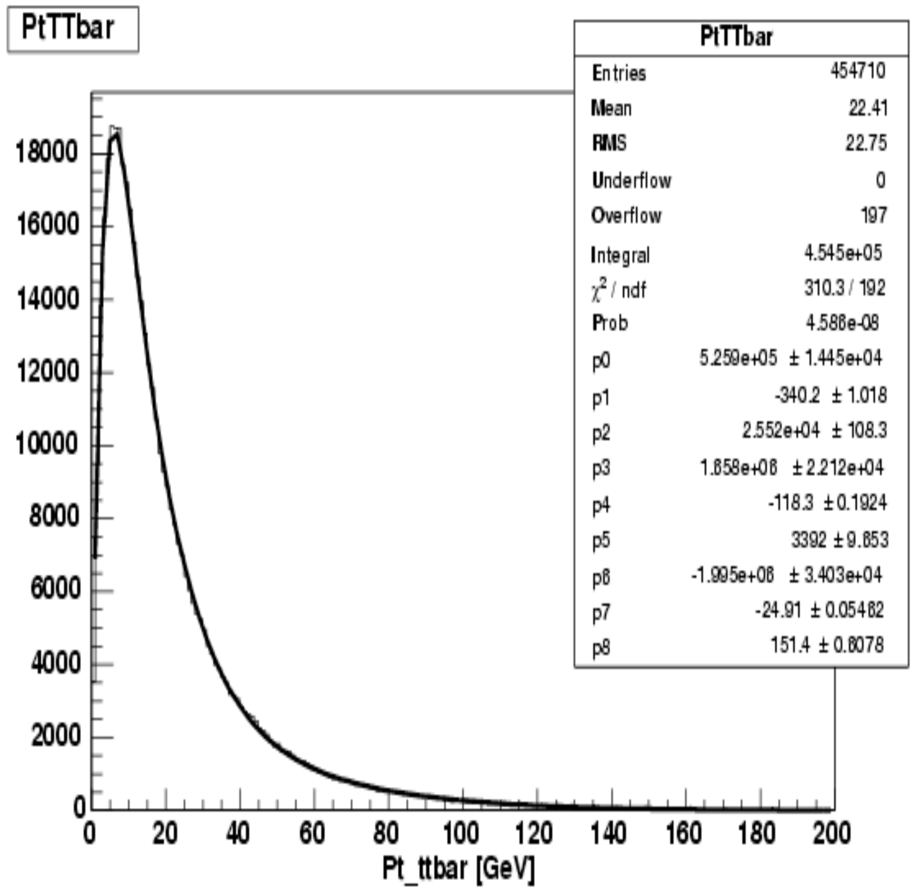
- **TF(p|j) is a probability that a parton of energy "p" has associated a jet of energy "j".**
  - B-jets & W-jets have different energy spectrum, and they are treated separately.
  - Sum of 2 gaussians used to fit the shape, normalized to 1.
  - Fit depends on the transverse momentum & pseudo-rapidity of partons
  - In the plot x-axis is "1-j/p"
- The distribution are built from Monte Carlo events where the jets were matched exclusively with partons.



Transverse Momentum of ttbar

Event probability density expression: $P(M_{top}) = \frac{\sum_{combi} \int d\sigma(p \mid j, M_{top}) \cdot TF(p \mid j) \cdot P_T(p)}{\sigma(M_{top})\varepsilon(M_{top}) N_{combi}}$

- **$P_T(p)$ is a weight following the shape of the transverse momentum of the ttbar final state**
  - Used the 6 quarks in the final state
  - Sum of 3 gaussians used to fit the shape, then normalize to 1.
- The distribution is built from Monte Carlo ttbar events.



Matrix Element Calculation

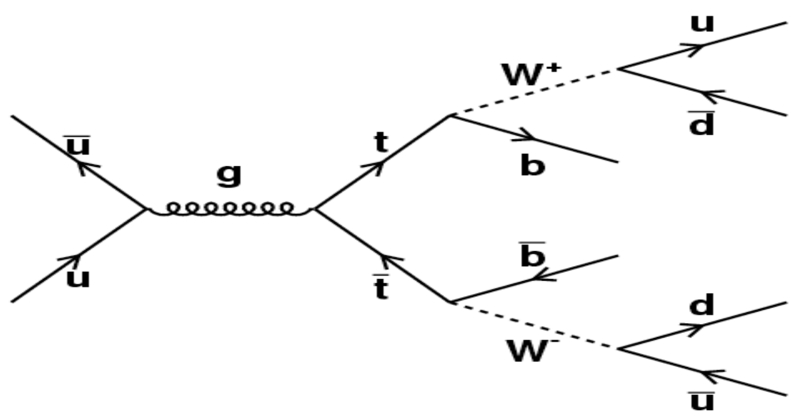
Event probability density expression: $P\left(M_{top}\right)=\frac{\sum_{combi}\int d\sigma\left(p\,|\,j,M_{top}\right)\cdot TF\left(p\,|\,j\right)\cdot P_T\left(p\right)}{\sigma\left(M_{top}\right)\varepsilon\left(M_{top}\right)N_{combi}}$

$$d\sigma(p\,|\,j,M_{top})=\int\frac{dz_a dz_b f(z_a)f(z_b)}{4E_aE_b|v_a-v_b|}\left|M(p\,|\,j,M_{top})\right|^2\prod_{i=1}^{6}\frac{d^3\vec{p}_i}{(2\pi)^3 2E_i}(2\pi)^4\delta^{(4)}(E_{fin}-E_{ini})$$

- **F($z_{a,b}$) is CTEQ5L proton PDF** (parton distribution function) with scale 175GeV.

- **Jets angles are assumed those of the partons**.

- **Matrix element squared is based on the tree level diagram uubar -> ttbar -> all hadronic decay**.
  - Monte Carlo events with ddbar or gluon-gluon interaction are not biased by this choice.
- *Massless quarks hypothesis simplifies calculation.*



Details of Integration

Event probability density expression: $P(M_{top}) = \frac{\sum_{combi} \int d\sigma(p \mid j, M_{top}) \cdot TF(p \mid j) \cdot P_T(p)}{\sigma(M_{top})\varepsilon(M_{top})N_{combi}}$

- Advantageous change of variables
  - b-quark momenta to x,y-components of the ttbar system momentum
    - Natural variables for the Pt of ttbar weight.
- **Use narrow width approximation for W bosons propagators.**
  - p,q momenta of W-decay quarks
  - ω a function of p,q-angles $\Omega=(\phi,\theta)$

$$P_W \xrightarrow{\Gamma_W << M_W} \frac{\pi}{M_W \Gamma_W} \cdot \frac{\delta(p - p^0)}{2q\omega_{qp}(\Omega_p, \Omega_q)}$$

$$p^0 = \frac{M_W^2}{2q\omega_{qp}}$$

- **4 integrals left over momenta**
  - Uniform grid of points 2 GeV away from each other in each dimension

- **Integration takes about 1hour/event.**
- **Use computing farm**

Tests of Matrix Element Calculation

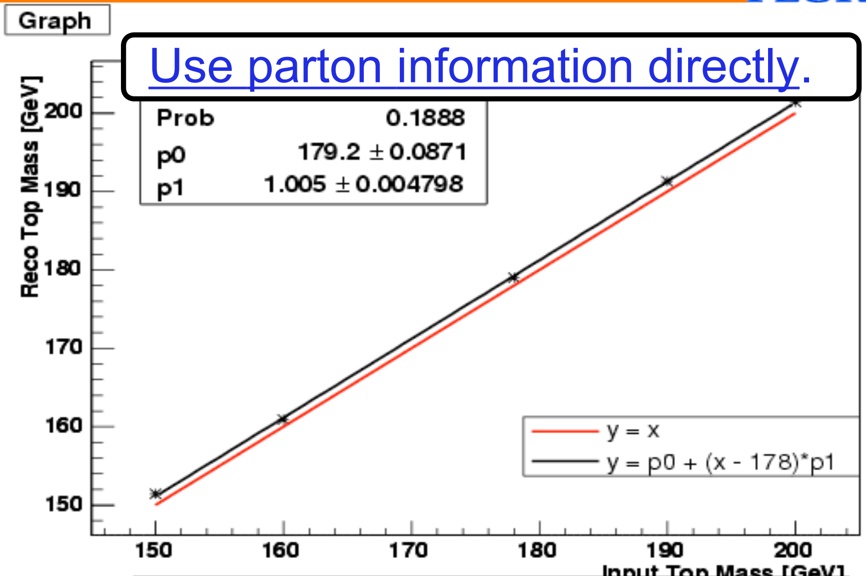
•Define a sample likelihood as product of event probability densities.

$$L(M_{top}) = \prod_{events} P(M_{top})$$

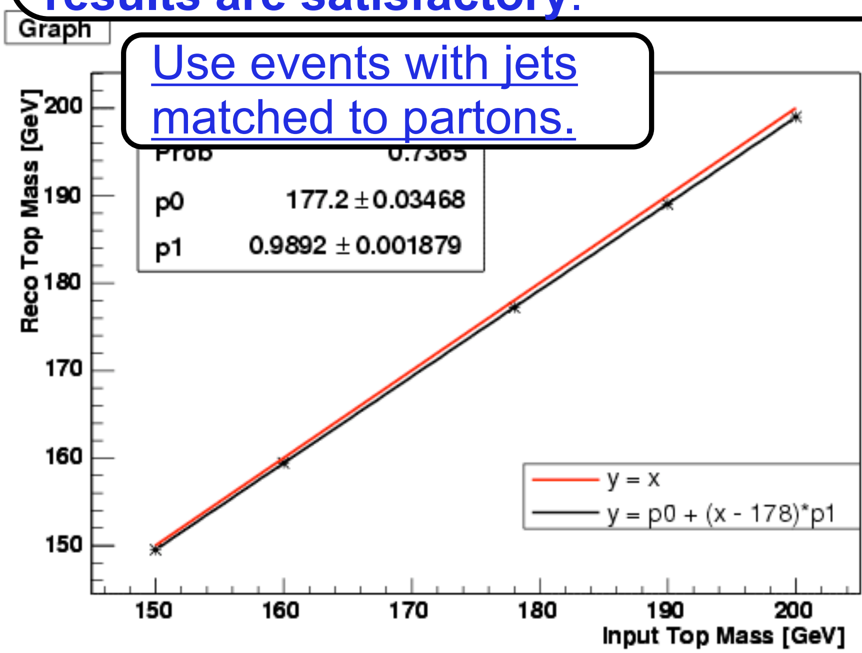
•Minimize the negative log of the sample likelihood in various scenarios.

•**Although there is a slight bias, the results are satisfactory**.

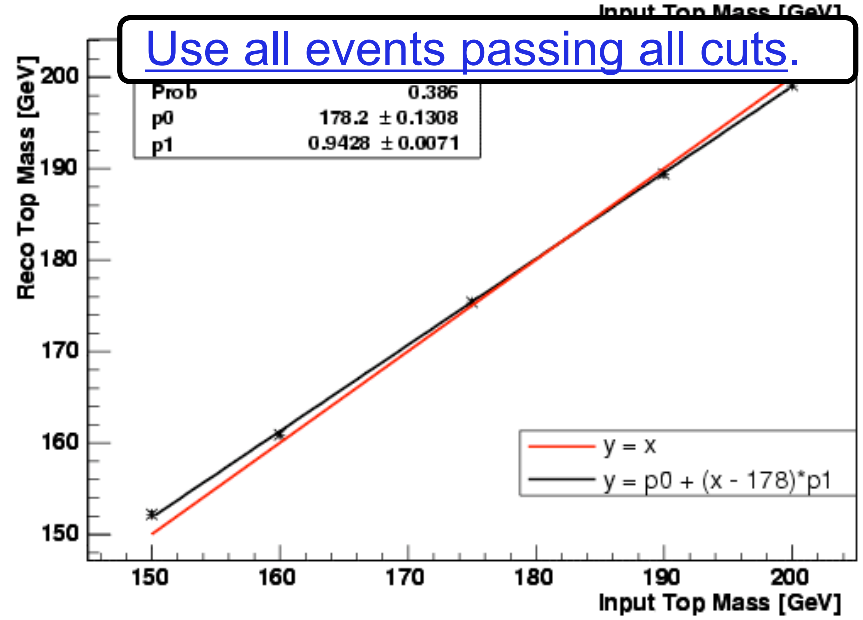
Use parton information directly.



Use events with jets matched to partons.



Use all events passing all cuts.



Final Event Selection

- **Clean-up cuts -> S/B ~ 1/1300**
  - Trigger emulation: Level2 SumEt>175GeV
  - Vertex: $|z|<60cm$ & $|z-z_p|<5cm$
  - Missing Et Significance: < 3 $(GeV)^{1/2}$
  - Tight lepton veto

- **Kinematical cuts -> S/B ~ 1/23**
  - Njets = 6 jets with $|eta|<2$ & Et>15GeV
  - Aplanarity+0.005SumEt$_3$ > 0.96
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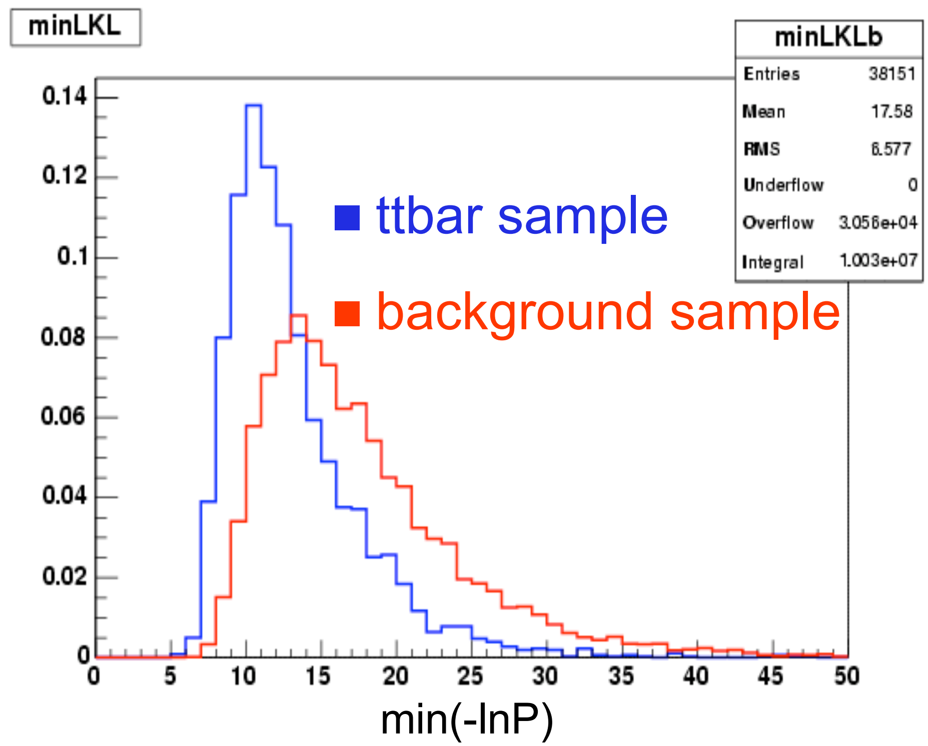
- **B-tagging -> S/B ~ 1/6**
  - Require at least 1 heavy flavor jet
  - Use SVX tagger



- ***ME probability cut -> S/B ~ 1/1***
  - min(-lnP) < 10
  - P is the probability density calculated via matrix element

Preview of Mass Reconstruction

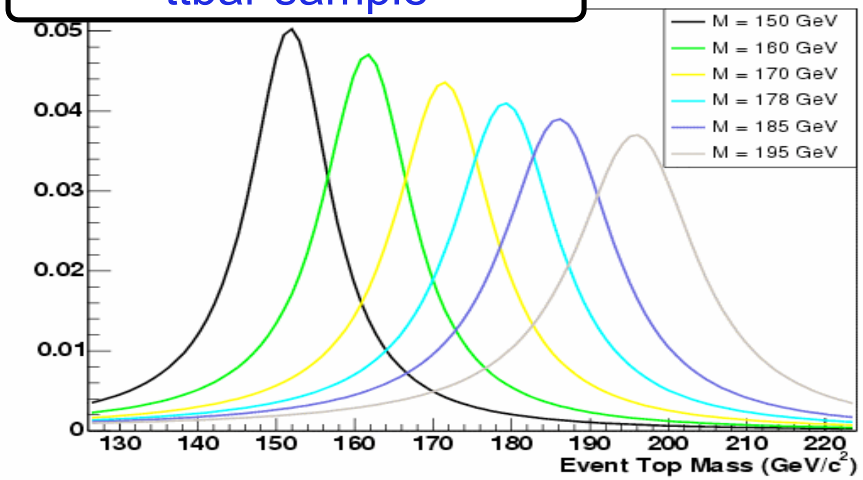
- **Employ a template technique**
  - *1st set of templates*
    - Parameterized distributions sensitive to variations in top quark mass
  - Define a variable, JES, related to jet energy scale.
    - *JES=change in jet energy quantified in units of uncertainty on the jet energy, σ_c.*
  - *2nd set of templates*
    - Parameterized distributions sensitive to variations in JES

- **Build a likelihood function using the two sets of templates**
- *Minimize the likelihood function with respect to top mass & JES simultaneously.*
  - Measuring JES is equivalent to an in situ calibration of the jet energy scale

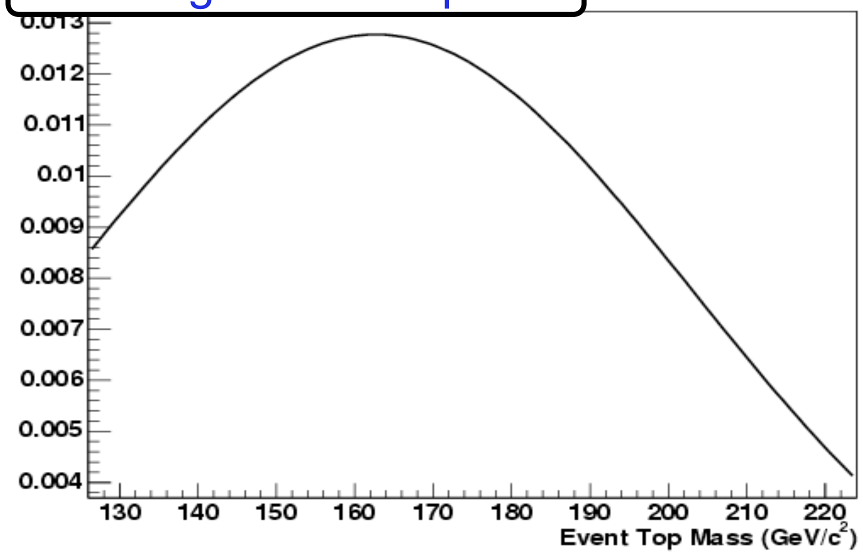
Event Top Mass Templates

- **The value of the mass M_0 for which -ln[P(M)] is minimized will be used to build top mass templates**
  - M_0 can be interpreted as the top mass as the event.
- These shapes are sensitive to changes in the value of top mass
  - ttbar shapes are fitted to Breit-Wigner times exponential.
    - The fit parameters depend linearly on true top mass & JES
  - Background shapes are fitted to a gaussian.
    - No mass or JES dependence.

ttbar sample



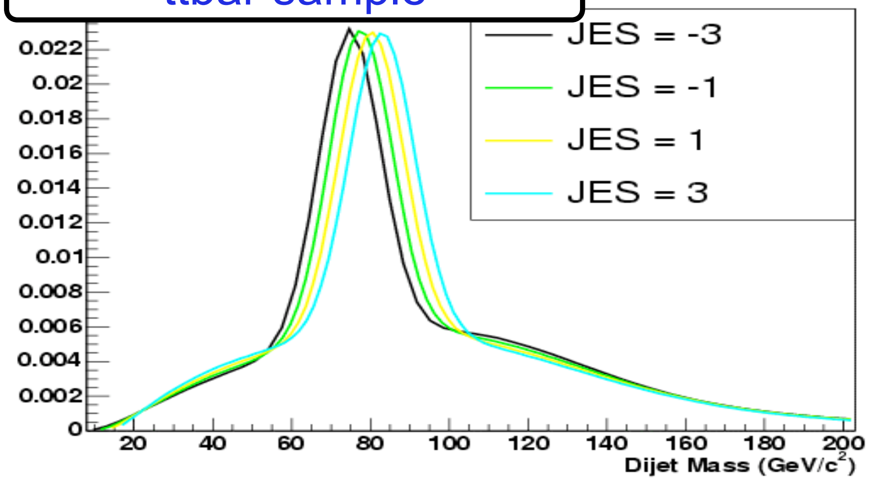
background sample



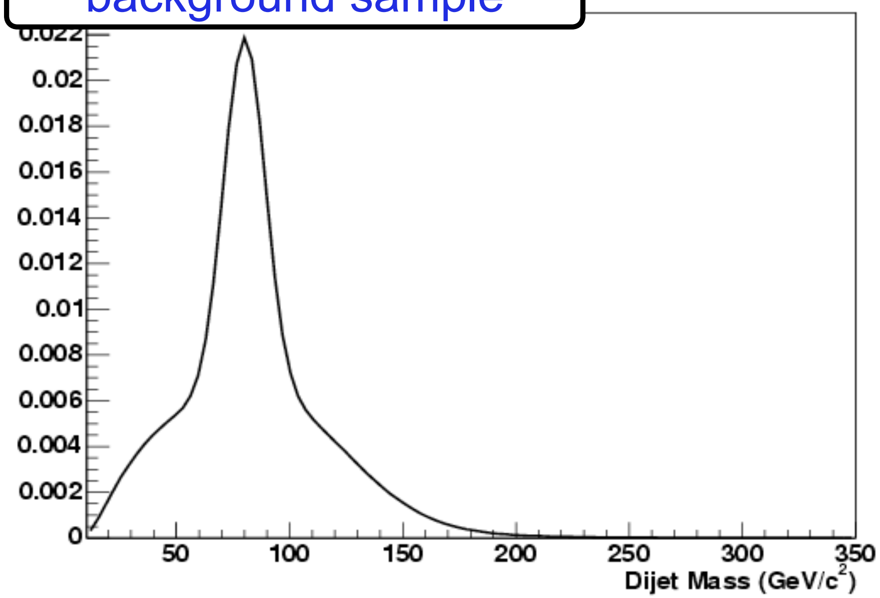
Dijet Mass Templates

- **The invariant mass of pairs M_{jj} of light flavor jets (untagged) used to build dijet mass templates**
    - M_{jj} can be interpreted as the W-boson mass as the event.
- These templates are sensitive to changes in JES
    - ttbar shapes are fitted to sum of two gausssians and gamma.
        - The fit parameters depend linearly on true top mass & JES
    - Background shapes are fitted to same function as for ttbar
        - No mass or JES dependence.

ttbar sample



background sample



Bi-dimensional Likelihood

- *Build a likelihood which depends on M_{top}, JES and number of events.*
  - Factorized for samples with different number of b-tagged jets.
  - Value of JES is constrained to a priori determination.

- *The dependence on M_{top} and JES comes for terms sensitive to variations in these values*
  - These terms are built with the help of the templates -> P^{top} & P^{W}

$$\boxed{L(M_{top}, JES, n) = L_{1tag} \times L_{2tag} \times L_{JES}}$$

$$L_{JES} = Gaus(JES \mid 0,1)$$

$$L_{n-tag} = L_{shape}^{top} \times L_{shape}^{W} \times L_{evt} \times L_{sig}$$

$$L_{shape}^{top} = \prod_{evt=1,N_{tot}^{obs}} \frac{n_s \cdot P_s^{top}\left(m_{evt}^{top} \mid M_{top}, JES\right) + n_b \cdot P_b^{top}\left(m_{evt}^{top}\right)}{n_s + n_b}$$

$$L_{shape}^{W} = \prod_{evt=\left(1,N_{tot}^{obs}\right)\times Ncombi} \frac{n_s \cdot P_s^{W}\left(m_{evt}^{W} \mid M_{top}, JES\right) + n_b \cdot P_b^{W}\left(m_{evt}^{W}\right)}{n_s + n_b}$$

- The total number of events is constrained to the observed value N_{tot}^{obs}.
- *The number of ttbar events is constrained to the expectation N_s^{exp} based on theoretical ttbar x-section of 6.7pb*

$$L_{evt} = Pois\left(n_s + n_b \mid N_{tot}^{obs}\right) \quad L_{sig} = Gaus\left(n_s \mid N_s^{exp}, \sigma_s^{exp}\right)$$

Events	1Tag	2Tags
Nobs	48	24
$N_s^{exp}(\sigma_{tt}=6.7pb)$	13	14
$(\sigma_s)^{exp}=\sqrt{(N_s^{exp})}$	3.6	3.7

Top Mass & JES Reconstruction

- Minimizing the 2D likelihood for Monte Carlo samples
  - *The mass and JES reconstruction shows a bias.*

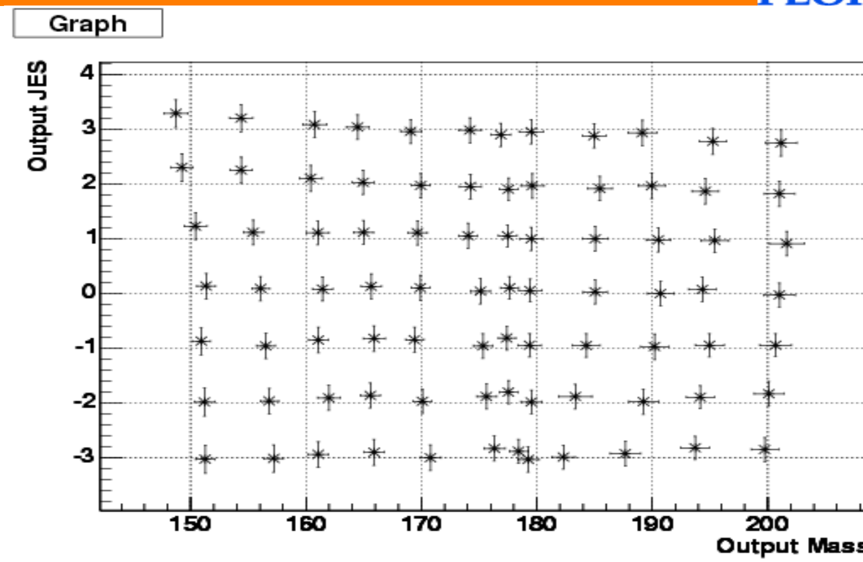
- Find the top mass & JES dependence of the bias
- **Calibrate the reconstruction to eliminate the bias.**
  - Assign a systematic uncertainty

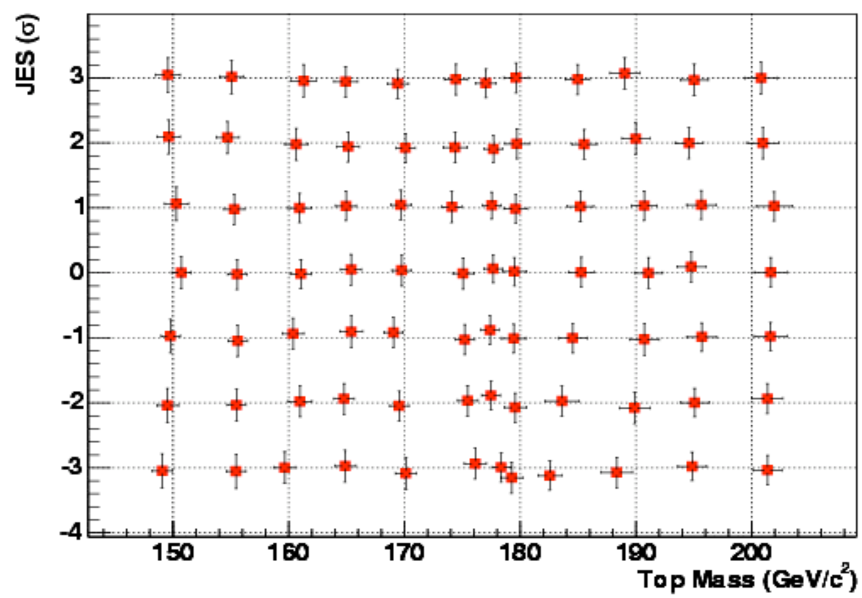
$$M_{out} = (a_1 + a_2 \cdot JES_{true}) + (a_3 + a_4 \cdot JES_{true}) \cdot (M_{true} - 175)$$

$$JES_{out} = (b_1 + b_2 \cdot M_{true}) + (b_3 + b_4 \cdot M_{true}) \cdot JES_{true}$$

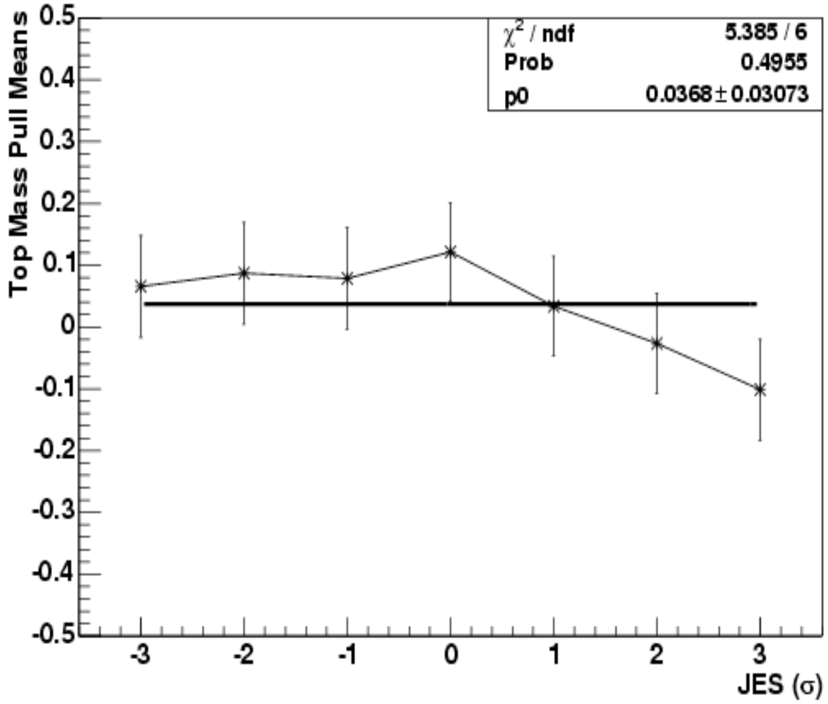
Label	Value
a1	175(0.1)
a2	-0.09(0.05)
a3	0.975(0.008)
a4	0.016(0.004)

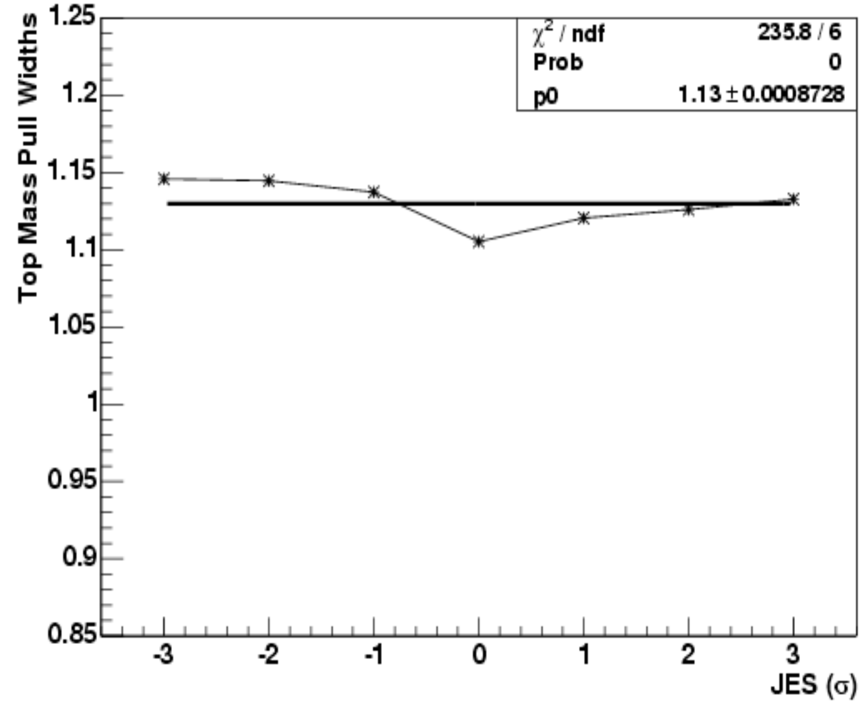
Label	Value
b1	0.6(0.3)
b2	-0.003(0.002)
b3	1.35(0.15)
b4	-2.1(0.8)x10^{-3}





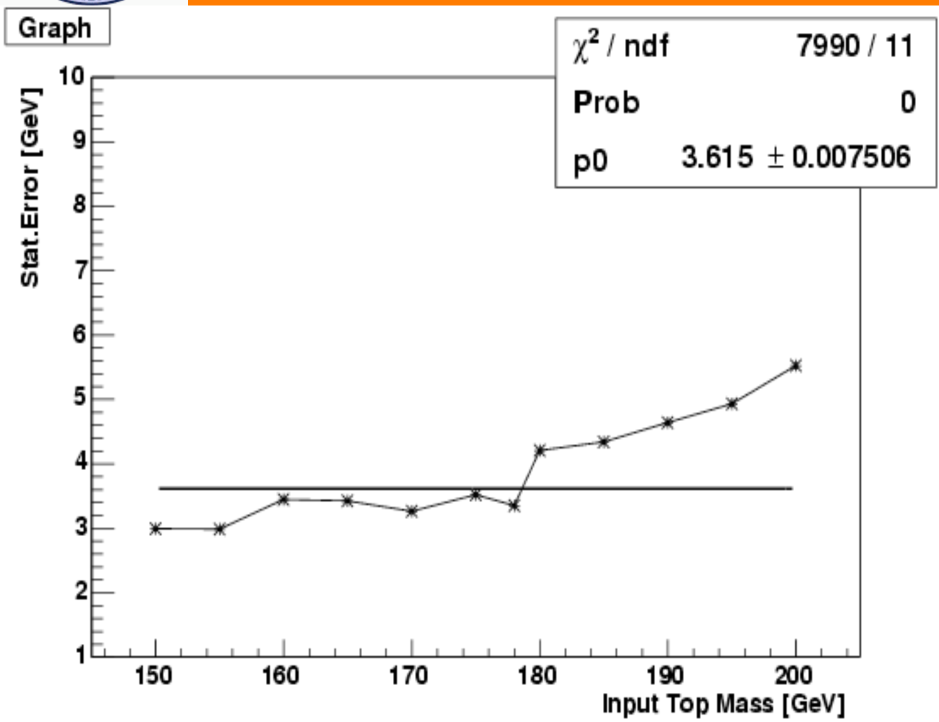
Pull Means & Widths

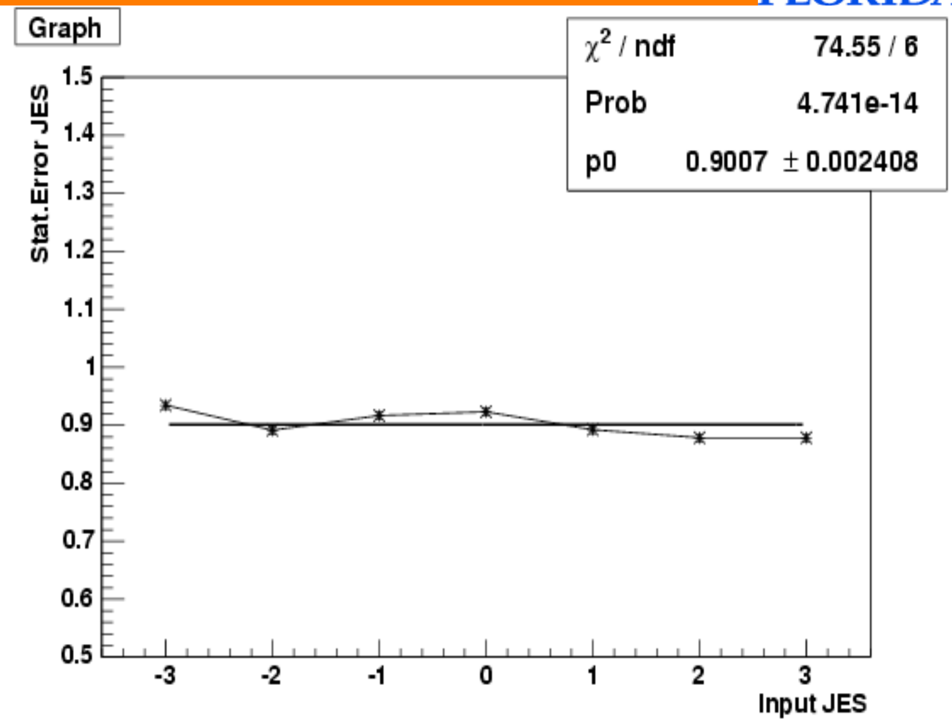




- Left: *Pull Mean Vs* JES shows no bias
- Right: *Pull Width Vs* JES indicates need for correction factor on statistical uncertainty of 1.13

Expected Sensitivity





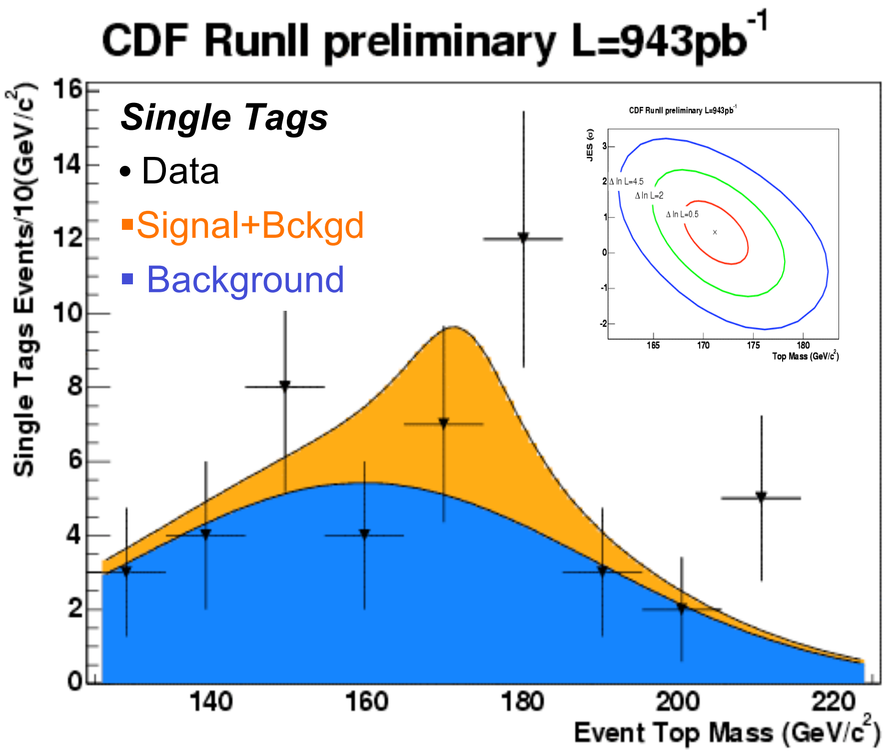
- Left: Expected statistical+JES uncertainty on top mass
- Right: Expected statistical uncertainty on JES
  - 10% improvement with respect to the *a priori* determination

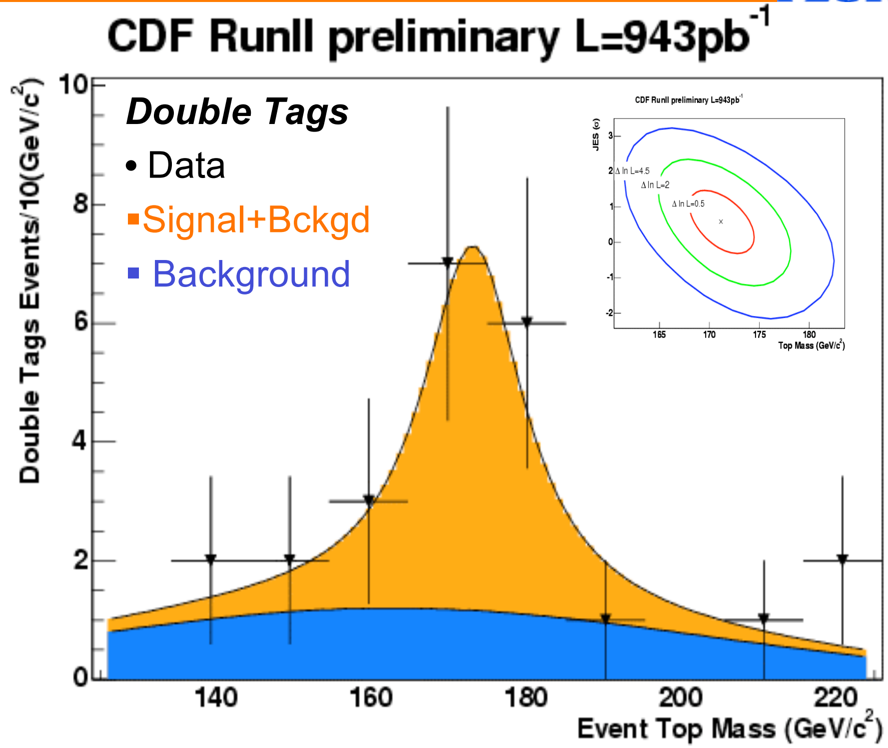
Systematic Uncertainties

- "ISR/FSR"- uncertainty due to the modeling of the initial/final state radiation in the Monte Carlo.
- "Fragmentation"- uncertainty due to different fragmentation models in Monte Carlo (Pythia vs Herwig)
- "Residual JES"- uncertainty due to the composite nature of the JES parameter (various effects form JES correction)

Source	Value(GeV/c^2)
ISR	0.3
FSR	1.2
PDF	0.5
Fragmentation	1.0
Method Calibration	0.2
Background Shape	0.9
Background Statistics	0.4
Sample Composition	0.1
B-JES	0.4
Residual JES	0.7
Total	**2.1**

Final Measurement



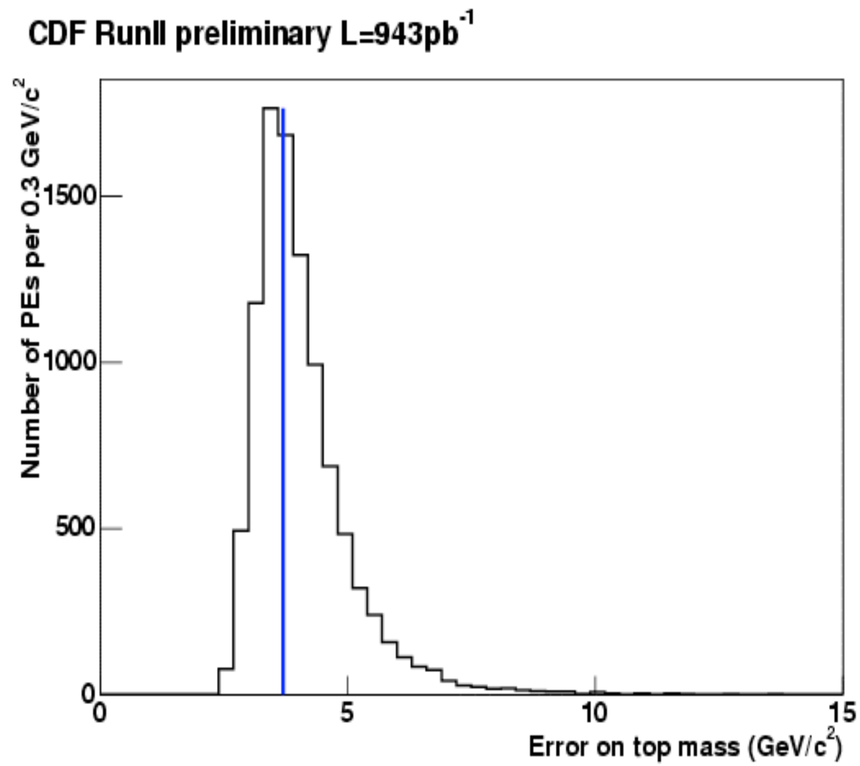


Mass = 171.1 ± 3.7 (stat.+JES) GeV/c²
JES = 0.5 ± 0.9 σ

Number of Events	1tag	2tag
Signal	13.2±3.7	14.1±3.4
Background	34.6±7.2	9.2±4.3

Consistency of the Statistical Error

- Using ttbar Monte Carlo
    - *form pseudo-experiments with the size determined by the data fit*
    - **41% of the PEs have lower uncertainty on top mass.**



Conclusion

- **M = 171.1 ± 2.8 (stat.) ± 2.4 (JES) ± 2.1(syst.) GeV/c^2**
- *This is the <u>most precise</u> measurement of the top mass in this channel*
  - Weighs 11% in the current world average
- *<u>First time simultaneous reconstruction</u>* in the *all hadronic channel* of the *top mass and JES*
- *Original interplay between matrix element technique and template method*
- *<u>First time use of matrix element technique in event selection</u>*
- The JES value is consistent with other analyses at CDF
  - *JES = 0.5 ± 0.9 σ*